

Cosmic ray propagation and interactions in the Galaxy

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Abstract

Cosmic ray propagation in the Galaxy is shortly reviewed. In particular we consider the self-consistent models of CR propagation. In these models CR streaming instability driven by CR anisotropy results in the Alfvénic turbulence which in turn determines the scattering and diffusion of particles.

Keywords:

cosmic rays, galactic wind, Galaxy

1. Introduction

Diffusion model of Ginzburg and Syrovatsky [1] was one of the first physically justified models of cosmic ray (CR) propagation. According to this model CR sources are supernova remnants (SNRs) which are situated in the Galactic disk. CR particles perform wandering in the tangled magnetic fields of the Galaxy. The propagation region of CRs is not limited by the Galactic disk but also contains some region above and below the Galactic disk - a so called Galactic halo.

Although CR diffusion was introduced phenomenologically it obtained later the theoretical basis [2]. Diffusive shock acceleration (DSA) [3, 4] in supernova remnants is considered now as a principle mechanism of CR production in the Galaxy. Its main predictions are in accordance with modern gamma-ray observations of supernova remnants [5].

CR confinement time in the Galaxy can be estimated using CR secondaries. CRs contain a significant amount of nuclei that are not abundant in nature. They appear after nuclear fragmentation of primary CRs in the interstellar medium. The measured Boron to Carbon CR ratio is shown in Fig.1 [6]. It is important that the ratio drops when the energy increases. This means that the residence time in the Galactic disk $t_{res}(E)$ is lower for higher energies. It is convenient to use a so called grammage $\Lambda(E) = \nu \rho t_{res}$ that is the mean amount of

matter transversed by CR particles. Here ν is the speed of the particles and ρ is the mean gas density in the Galactic disk. The measured secondary to primary ratio can be used to estimate the grammage $\Lambda(E)$. This gives $\Lambda(E) \propto E^{-\mu}$ at energies higher than several GeV per nucleon with the index μ being between 0.3 and 0.6.

In the pure diffusion model the grammage and CR diffusion coefficient are related as $\Lambda(E) \propto D^{-1}$, so we expect that CR diffusion coefficient increases with energy as $D \propto E^\mu$. The situation is more complicated in the models which take into account other processes like reacceleration, advection etc.

2. Cosmic ray diffusion in Galactic magnetic fields.

CR diffusion is determined by magnetic inhomogeneities. The scattering of particles occurs via interaction with random magnetic fields δB with the scales comparable with the gyroradius of particles. The scattering frequency ν can be estimated as

$$\nu \sim \Omega \frac{\delta B^2}{B^2} \quad (1)$$

Here B is the regular magnetic field and $\Omega = qBv/pc$ is the gyrofrequency of particles with the electric charge q and momentum p . The diffusion coefficient along the

regular magnetic field D_{\parallel} is given by the relation $D_{\parallel} = v^2/3v$.

According to modern theories the MHD turbulence have two main components: anisotropic quasi-Alfvénic incompressible fluctuations with $k^{-5/3}$ spectrum and the isotropic magnetosonic waves with the spectrum $k^{-3/2}$ [7].

The quasi-Alfvénic magnetic inhomogeneities are elongated along the local magnetic field, so when their length is of the order of particle gyroradius the corresponding perpendicular scale is small. That is why the scattering by the quasi-Alfvénic component is not effective [9].

The second isotropic magnetosonic component is good enough for scattering. The corresponding energy dependence of diffusion coefficient $D_{\parallel} \sim vp^{1/2}$ is in good agreement with measured secondary to primary ratios of Galactic CRs. This possibility is considered as a good physical solution for the propagation problem [8].

However the magnetosonic component exists only when MHD approximation of interstellar turbulence is used. Magnetosonic waves are damped via the linear Landau damping [10] in the more justified plasma description of interstellar turbulence. This damping prevents nonlinear energy transfer of energy to smaller scales for magnetosonic waves. The Landau damping is weaker for waves propagating at small angles relative to the magnetic field. However this does not help because the rate of nonlinear transfer of energy to small scales is also weaker at these angles. So only strongly oblique magnetosonic waves with their high phase velocities can avoid the damping and can transfer the energy to smaller and smaller scales. But their obliqueness again will result in the inefficient scattering of CR particles.

We conclude that the main components of interstellar turbulence can not provide the scattering of the main part of Galactic CRs with energies below 1 PeV. For higher energies gyroradius of particles is above 0.1 pc and these particles in principle can be scattered by the background turbulence.

3. Cosmic ray streaming instability and damping of waves

In this regard another sources of magnetic turbulence should be considered. The best candidate is a so called streaming instability driven by anisotropic CR distribution. Its importance for CR propagation was recognized

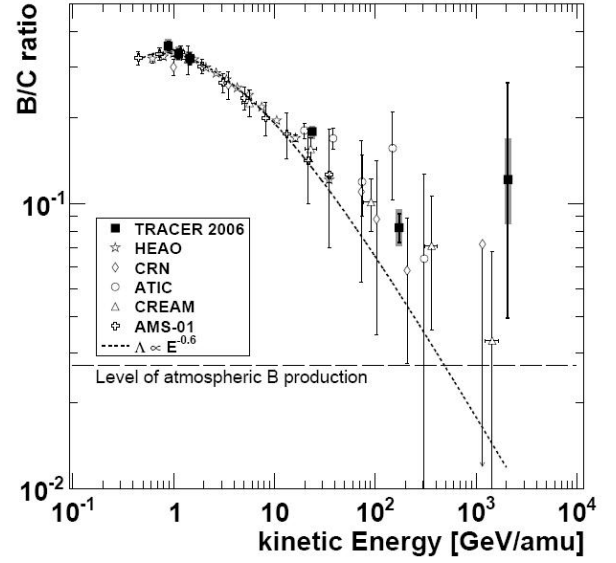


Figure 1: Measurements of B/C ratio performed in different experiments [6].

many decades ago [12, 13, 14, 15, 16]. The growth rate of unstable Alfvén waves is given by the equation [17]

$$\Gamma_{CR} \sim \Omega_i \frac{N(r_g > k^{-1})}{n} \left(\frac{u_{cr}}{v_A} - 1 \right). \quad (2)$$

Here Ω_i is the gyrofrequency of thermal ions, n is the plasma number density and $N(r_g > k^{-1})$ is the number density of CR particles with gyroradii $r_g = pc/qB$ higher than the inverse wavenumber k . The instability develops when the mean velocity of CR distribution u_{cr} is higher than the Alfvén velocity v_A .

CR streaming produces waves with the scale k^{-1} comparable with the gyroradius of particles. The particles in turn are scattered by these waves.

Alfvén waves produced by GeV particles have the growth rate $\Gamma \sim 10^{-10} \text{ s}^{-1}$. So the growth time is only 300 years that is this time is very short in comparison with other Galactic time scales.

Some damping mechanisms must be used to prevent the strong growth of waves. In the warm partially ionized regions of the Galactic disk the damping rate of Alfvén waves by neutral atoms is given by [14]

$$\Gamma_n = \frac{1}{2} v_{th} \sigma_{ex} n_n \quad (3)$$

Here n_n is the number density of neutrals, v_{th} is the thermal velocity of plasma ions and neutral atoms and σ_{ex}

is the charge exchange cross-section. For the charge exchange cross-section $\sigma_{ex} \sim 10^{-14} \text{ cm}^2$ and thermal velocity $v_{th} \sim 10 \text{ km s}^{-1}$ the damping rate is $\Gamma \sim 10^{-9} \text{ s}^{-1}$, that is the streaming instability is suppressed in the warm interstellar medium. If so one can expect the weak scattering of particles and the large CR diffusion coefficient in the Galactic disk.

However neutral atoms absent in the ionized parts of the Galactic disk and in the Galactic halo where CRs propagate. In these regions the existence of the damping of Alfvén waves by background anisotropic MHD turbulence was recognized recently [11, 9]. The plasma motions of the background turbulence mix the plasma material in the perpendicular to the local magnetic field directions. As a result the perpendicular wave number of the test Alfvén waves increases. CR scattering by such waves becomes inefficient while the waves eventually absorbed by the background turbulence. The rate of this process for oblique waves can be estimated as

$$\Gamma_b \sim \frac{\omega}{(k_{\perp} L)^{1/3}}, \quad k_{\parallel} \sim k_{\perp} \quad (4)$$

Here $\omega = v_A |k_{\parallel}|$ is the wave frequency, k_{\parallel} and k_{\perp} are the wavenumbers in the parallel and perpendicular to the local magnetic field direction, L is the scale of the background turbulence. For waves resonant with GeV CR particles $k \sim 10^{12} \text{ cm}^{-1}$ and for the main scale $L = 100 \text{ pc}$ we found the damping rate $\Gamma_b \sim 10^{-9} \text{ s}^{-1}$. That is the streaming instability of oblique waves is suppressed in the ionized regions of the Galactic disk.

However CR streaming produces waves predominantly in the direction of the local magnetic field. For this case the damping by background turbulence is weaker and is given by

$$\Gamma_b \sim \frac{\omega}{(k_{\parallel} L)^{1/2}} \quad (5)$$

Now the estimate of the damping rate $\Gamma_b \sim 10^{-10} \text{ s}^{-1}$ is comparable with the expected value for the wave growth of the streaming instability. For higher energies the damping by the background turbulence is stronger than the streaming instability. That is why we conclude that CR streaming instability can be suppressed in the ionized regions of the Galactic disk.

This consideration leaves the Galactic halo as the place where CR streaming instability can operate. It is expected that sources of background turbulence are weaker there. In addition the streaming instability is faster in the Galactic halo because of the low plasma density (see Eq. (2)).

There exists nonlinear damping of waves in addition to the linear kinds of damping considered above. Thermal ions can interact with moving magnetic mirrors appearing when Alfvén waves present in the plasma. The gain of the ion energy is accompanied by the corresponding damping of the waves [18, 19, 20, 21, 22, 23]. The damping rate can be estimated as

$$\Gamma_{nl} \sim \omega \delta \frac{k W(k)}{B^2 / 4\pi} \quad (6)$$

Here the spectral energy density of waves $W(k)$ is normalized as $\langle \delta B^2 \rangle = 4\pi \int dk W(k)$, δ is dimensionless parameter of the order of unity. The nonlinear damping rate depends on the wave spectrum and can be used to determine the level of the Alfvén turbulence generated by CR streaming instability.

4. Galactic wind driven by cosmic rays

CR influence on the Galaxy is not reduced to generation of Alfvénic turbulence. CR energy density is comparable with the gas and magnetic energy densities in the Galactic disk. It is expected that the propagation region of CRs is significantly broader than the Galactic disk. If so the dynamical effects of CRs will be stronger in the Galactic halo where gas density and pressure are lower. It is possible that CR pressure gradient drives outflow from the Galactic disk and from the Galaxy - a so called Galactic wind [24, 25, 26, 27]. The expected geometry of the wind flow is shown in Fig.2. Galactic wind flows along the surface S . The frozen magnetic field \mathbf{B} is tangent to this surface. At large distances from the Galaxy the field is almost azimuthal due to rotation of the Galaxy. This azimuthal configuration results in the better confinement of high-energy cosmic rays.

For illustration we show the results of the Galactic wind calculations [30] in Fig.3. The damping of Alfvén waves produced by CR streaming instability results in the strong gas heating in the Galactic halo. At low heights this heating is balanced by radiative cooling of the gas. However at large heights the gas number density is low and the cooling is not effective. As a result the gas temperature is of the order of one million degrees at large heights. It is interesting that such a halo of the hot gas with a similar density profile is indeed observed now via measurements of OVII line absorption [28].

5. Self-consistent models of CR propagation

Steady state CR transport along the surface S is described by the following equation for isotropic part of

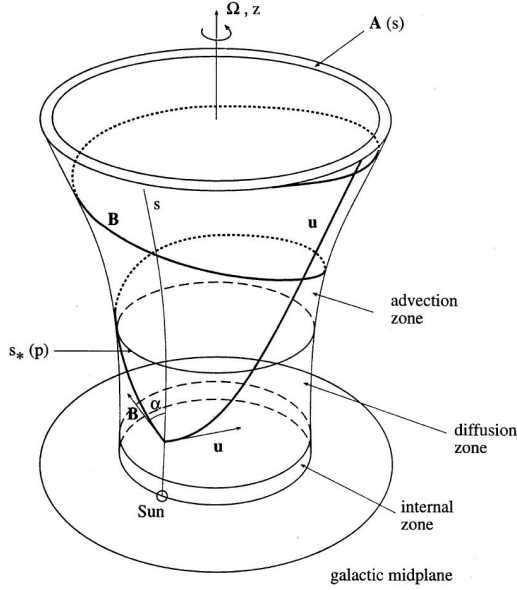


Figure 2: Geometry of the flux tube and magnetic field along the surface S . Vectors of magnetic field \mathbf{B} and gas velocity \mathbf{u} are tangent to the surface S . α is the angle between the magnetic field and meridional direction.

CR momentum distribution $N(p)$ [29]:

$$\frac{1}{A(s)} \frac{\partial}{\partial s} A(s) D_{\parallel} \cos^2 \alpha \frac{\partial N}{\partial s} - (u + v_a) \frac{\partial N}{\partial s} + \frac{p}{3} \frac{\partial N}{\partial p} \frac{1}{A(s)} \frac{\partial}{\partial s} A(s) (u + v_a) + 2Q(p) \delta(s) = 0. \quad (7)$$

Here $Q(p)$ is the half of the surface CR source power and $v_a = \pm v_A \cos \alpha$ is the meridional component of the Alfvén velocity directed away from the Galactic disk.

Let us assume that CR sources in the disk have power-law dependence on momentum

$$Q(p) = \frac{\varepsilon}{4\pi c (mc)^4} \left(\frac{p}{mc} \right)^{-\gamma} H(p_m - p). \quad (8)$$

Here m is the proton mass, p_m is the maximum momentum of CR sources, and the parameter ε determines the surface flux of CR energy F_c :

$$F_c = \varepsilon \int_0^{p_m/mc} y^{2-\gamma} dy \left(\sqrt{y^2 + 1} - 1 \right). \quad (9)$$

We shall assume that CR diffusion is determined by self-excited Alfvén waves. The condition of the local balance for the wave generation and damping $\Gamma_{CR} = \Gamma_{nl}$

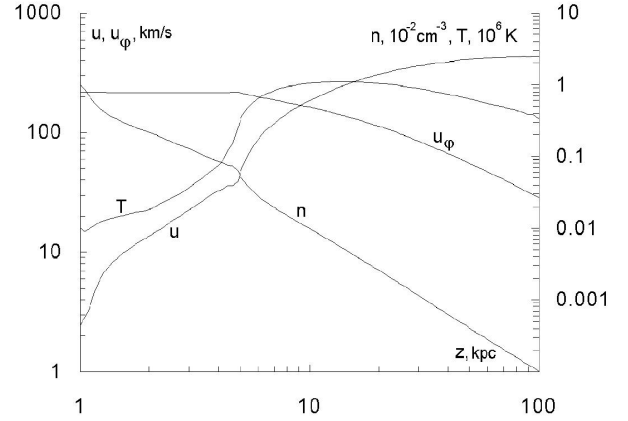


Figure 3: Dependence of meridional and azimuthal components of the gas velocity u and u_ϕ , the gas number density and temperature T on the height above the Galactic disk z . The following parameters were fixed at 1 kpc above the midplane of the disk: $P_{c0} = 5 \cdot 10^{-13}$ erg cm^3 , $n_0 = 10^{-2} \text{ cm}^{-3}$, $B_0 = 2 \cdot 10^{-6} \text{ G}$.

can be used to obtain the spectrum of waves $W(k)$. It in turn determines CR diffusion coefficient [29]:

$$D_{\parallel} = \frac{8\delta\gamma(\gamma-2)}{9\pi^2} \frac{c^2}{\Omega_i} \frac{B^2/4\pi}{\varepsilon/c} \left(\frac{p}{mc} \right)^{\gamma-3} \times A(s) \cos \alpha, \quad (10)$$

The numerical value of D_{\parallel} for γ close to 4 is given by expression

$$D_{\parallel} = 1.8 \cdot 10^{26} \delta \frac{\text{cm}^2}{\text{s}} \left(\frac{p}{mc} \right)^{\gamma-3} B_{\mu\text{G}} \varepsilon_{-6}^{-1} A(s) \cos \alpha. \quad (11)$$

Here we normalize the parameter ε to its characteristic value $10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1}$.

5.1. self-consistent diffusion models

These equations can be used in self-consistent diffusion models of CR propagation [12, 13, 14, 15, 16, 31].

Since the observable spectrum $N_{obs}(p) \sim Q(p)/D_{\parallel}$ we find that

$$N_{obs}(p) \sim p^{-(2\gamma-3)} \quad (12)$$

To obtain the observable $N_{obs} \sim p^{-4.7}$ we should take the source spectrum $p^{-3.85}$. The diffusion coefficient is rather strong function of energy $D_{\parallel} \sim p^{0.85}$. It is interesting that such a hard spectrum of CR sources is indeed predicted by nonlinear DSA with efficient CR acceleration (see e.g. [32]).

5.2. self-consistent diffusion-advection model

The advection of CRs in the galactic wind flow was taken into account by Ptuskin et al. [29] In this model at small distances $s < s_*(p)$ diffusion dominates advection while at large distances the opposite inequality is valid. The distance to the diffusion-advection boundary $s_*(p)$ can be found from relation $(u + v_a)s_* \sim D_{\parallel} \cos^2 \alpha$. It is possible to use the expression for diffusion coefficient (10) for this estimate. It should be noted that the factor $A(s)B \cos \alpha$ is s -independent in the Galactic wind flow. This means that the self-consistent parallel diffusion coefficient D_{\parallel} does not depend on s .

At distances smaller than the Galactic radius R_g CRs are advected with Alfvén velocity that is approximately proportional to the height s . The height of diffusion-advection boundary is then $s_*(p) \propto p^{(\gamma-3)/2}$. The spectrum in the disk is $N_{obs}(p) \propto Q(p)/v_a(s_*) \propto p^{-\frac{3}{2}(\gamma-1)}$.

At large distances CR particles are advected by the wind with almost constant speed, the magnetic field is almost azimuthal and $\cos \alpha \propto s^{-1}$. This gives the distance to the diffusion-advection boundary $s_*(p) \propto p^{(\gamma-3)/3}$. The observable spectrum $N_{obs} \propto Q(p)/us_*^2 \propto p^{-\frac{5}{3}\gamma+2}$.

We combine these cases as

$$N_{obs}(p) \propto \begin{cases} p^{-\frac{3}{2}(\gamma-1)}, & p < p_g \\ p^{-\frac{5}{3}\gamma+2}, & p > p_g \end{cases} \quad (13)$$

Here p_g is the momentum of particles with the height of diffusion-advection boundary that is comparable with the Galactic radius $s_*(p_g) = R_g$. The rough estimate from Eq. (11) is $p_g \sim \text{TeV}/c$. So to obtain the observed spectrum $p^{-4.7}$ one should have the spectral index in the source $\gamma = 4.13$ at $p < \text{TeV}/c$ and $\gamma = 4.02$ at $p > \text{TeV}/c$. Note that the concave spectrum of CR sources is indeed predicted by nonlinear DSA.

The parameter ε should be adjusted to reproduce the observed CR intensity. This gives the value close to $\varepsilon \approx 10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1}$ [29]. The corresponding Galactic CR luminosity $L_{CR} = 2\pi F_c R_g^2 \approx 1.3 \cdot 10^{41} \text{ erg s}^{-1}$ or 13% of the mechanical power of Galactic supernovae. The energetic dependence and the numerical value of grammage $\Lambda(E) \propto E^{-0.57}$ are also in accordance with observations [29].

Using the value of diffusion coefficient one can estimate the size of the diffusion region $s_*(p)$. The size $s_* = 1 \text{ kpc}$ corresponds to the energy 10 GeV, the Galactic scale $s_* = 15 \text{ kpc}$ corresponds to 1 TeV. At large distances $s_* \propto p^{1/3}$ and the energy 10^6 GeV corresponds to the size $s_* = 150 \text{ kpc}$.

6. Cosmic ray anisotropy problem

Self-consistent models described above have hard spectra of CR sources close to p^{-4} . This results in fast increase of CR anisotropy with energy. The estimates show that the anisotropy of CR protons might be of the order of unity at PeV energies [33]. The mixed CR composition probably will make the anisotropy lower close to 0.1 but still one hundred times higher than the observable anisotropy 10^{-3} .

One of possibilities to avoid this contradiction is related with the small diffusion coefficient D_{in} in the Local Bubble where the Sun is situated. The Local Bubble is a large cavity with the size 100 pc. It was created by OB association via stellar winds and supernova explosions several million years ago. Since the cavity is filled by the hot ionized gas the MHD waves in this region are not damped due to presence of neutrals contrary to the warm ionized medium in the Bubble surroundings.

Under these conditions the anisotropy inside the Bubble is D_{out}/D_{in} times smaller than the anisotropy outside the Bubble [33]. Here D_{out} is the diffusion coefficient outside the Bubble.

The main scale of turbulence can be 1 pc in the Local Bubble. The free path of CR particles is of the same order. Outside the Bubble the main scale and the free path of particles can be of the order 100 pc. So the ratio of the diffusion coefficients close to one hundred is possible. This reduces the CR anisotropy to observable values.

References

- [1] Ginzburg, V.L., Syrovatskii, The origin of cosmic rays, 1969, New York : Gordon and Breach
- [2] Berezhinskii, V.S. et al., Astrophysics of Cosmic Rays, 1990, North Holland, NY
- [3] Krymsky, G.F. A regular mechanism for the acceleration of charged particles on the front of a shock wave, 1977, Soviet Physics-Doklady, 22, 327-329
- [4] Bell, A.R. The acceleration of cosmic rays in shock fronts - I, 1978, Mon. Not. Royal Astron. Soc. 182, 147-156
- [5] Rieger, F., de Oña Wilhelmi, E., Aharonian, F., TeV astronomy, 2013, Frontiers of Physics, 8, 714-747
- [6] Obermeier, A., Boyle, R., Hörandel, J., Müller, D., The Boron-to-carbon Abundance Ratio and Galactic Propagation of Cosmic Radiation, 2012, Astrophys. J., 752, 69-75
- [7] Brandenburg, A., Lazarian, A., Astrophysical Hydromagnetic Turbulence, 2013, Space Science Reviews, 178, 163-200
- [8] Strong, A.W., Moskalenko, I.V., Ptuskin, V.S. Cosmic-Ray Propagation and Interactions in the Galaxy, 2007, Annual Review of Nuclear and Particle Systems 57, 285-327
- [9] Yan, H., Lazarian, A., Cosmic-Ray Scattering and Streaming in Compressible Magnetohydrodynamic Turbulence, 2004, Astrophys. J. 614, 757-769
- [10] Ginzburg, V.L., Propagation of Electromagnetic Waves in Plasma, 1961, New York: Gordon & Beach

- [11] Farmer, J.F., Goldreich, P., Wave Damping by Magnetohydrodynamic Turbulence and Its Effect on Cosmic-Ray Propagation in the Interstellar Medium, 2004, *Astrophys. J.* 604, 671-674
- [12] Kulsrud, R.M., Pearce, W.P. The effect of wave-particle interactions on the propagation of cosmic rays, 1969, *Astrophys. J.* 156, 445-470
- [13] Wentzel, D.G. The Propagation and anisotropy of cosmic rays. I. Theory for steady streaming, 1969, *Astrophys. J.*, 156, 303-314
- [14] Kulsrud, R.M., Cesarsky, C.J. The effectiveness of instabilities for the confinement of high energy cosmic rays in the Galactic disk, 1971, *Astrophys. Lett.* 8, 189
- [15] Ginzburg, V.L., Ptuskin, V.S., Tsytovich, V.N. The role of plasma effects in propagation and isotropisation of cosmic rays in the Galaxy, 1973, *Astrophys. Space Sci.* 21, 13-38
- [16] Skilling, J. Cosmic ray streaming. III - Self-consistent solutions, 1975, *Mon. Not. Royal Astron. Soc.* 173, 255-269
- [17] Lerche, I. Unstable magnetosonic waves in a relativistic plasma, 1967, *Astrophys. J.* 147, 689-696
- [18] Lee, M.A., Völk, H.J. Damping and non-linear wave-particle interactions of alfvén-waves in the solar wind, 1973, *Astrophys. and Space Sci.* 24, 31-42
- [19] Achterberg, A. On the propagation of relativistic particles in a high beta plasma, 1981, *Astron. Astrophys.* 98, 161-172
- [20] Kulsrud, R.M. Plasma in astrophysics, 1982, *Physica Scripta* 2/1, 177-181
- [21] Achterberg, A., Blandford, R.D. Transmission and damping of hydromagnetic waves behind a strong shock front: implications for cosmic ray acceleration, 1986, *Mon. Not. Royal Astron. Soc.* 218, 551-575
- [22] Fedorenko, V.N., Ostryakov, V.M., Polyudov, A.N., Shapiro, V.D. Induced scattering and two quantum absorption of Alfvén waves in plasma with arbitrary beta, 1988, Preprint N 1267 A.F.Ioffe Phys.Tech. Inst., Leningrad
- [23] Zirakashvili, V.N., Induced Scattering and Two-Photon Absorption of Alfvén Waves with Arbitrary Propagation Angles, 2000, *JETP* 90, 810-816
- [24] Ipavich, F.M. Galactic winds driven by cosmic rays, 1975, *Astrophys. J.* 196, 107-120
- [25] Breitschwerdt, D., McKenzie, J.F., Völk, H.J. Galactic Winds. I - Cosmic ray and wave-driven winds from the Galaxy, 1991, *Astron. Astrophys.* 245, 79-98
- [26] Zirakashvili, V.N., Breitschwerdt, D., Ptuskin, V.S., Völk, H.J. Magnetohydrodynamical galactic wind driven by cosmic rays in a rotating galaxy, 1996, *Astron. Astrophys.* 311, 113-126
- [27] Everett, J.E., Zweibel, E.G.; Benjamin, R.A., et al. Does the Milky Way launch a large-scale wind? 2007, *Astrophys. and Space Science*, 311, 105-110
- [28] Miller, M.J., Bregman, J.N., The Structure of the Milky Way's Hot Gas Halo, 2013, *Astrophys. J.*, 770, 118-130
- [29] Ptuskin, V.S., Zirakashvili, V.N., Breitschwerdt, D., Völk, H.J. Transport of relativistic nucleons in a galactic wind driven by cosmic rays, 1997, *Astron. Astrophys.* 321, 434-443
- [30] Zirakashvili, V.N., Ptuskin, V.S., Völk, H.J. 2002, *Bull. Russian Ac. Sci.* 66, 1606-1608 (in Russian)
- [31] Alloisio, R., Blasi, P., Propagation of galactic cosmic rays in the presence of self-generated turbulence, 2013, *Journal of Cosmology and Astroparticle Physics*, 7, 1-23
- [32] Berezhko, E.G., Völk, H.J., Spectrum of Cosmic Rays Produced in Supernova Remnants, 2007 *Astrophys. J.* 661, L175-L178
- [33] Zirakashvili, V.N. Cosmic ray anisotropy problem, 2005, *Intern. Journal of Modern Physics A* 20, 6858-6860